microGPS: On-orbit Demonstration of a New Approach to GPS for Space Applications

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BIOGRAPHY

Jeffrey Srinivasan received his B.A. degree in Engineering and Applied Sciences with honors from Harvard College in 1983 and his M.S. degree in Electrical Engineering from University of Southern California in 1988. He joined the technical staff at JPL in 1983 and is currently a Technical Group Leader. He was instrumental in various hardware/software aspects of the microGPS development.

Yoaz Bar-Sever received his Ph.D. in Applied Mathematics from the Technion - Israel Institute of technology, in 1987. From 1987 to 1989 he was a post-doctoral fellow at the Department of Applied Mathematics at Caltech. In 1993 he received an additional Master degree in Electrical Engineering from the University of Southern California. He joined JPL in 1989 where he has been involved in GPS technology development and its geophysical applications. He now supervises the Earth Orbiter Systems Group at JPL.

Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems.

Stephen M. Lichten received a B.A. from Harvard in 1978 and a Ph.D. from Caltech in 1983. He then joined the Jet Propulsion Laboratory (JPL) in 1983, initially working on very long baseline interferometry and precision GPS orbit determination. In 1996, he helped develop the Inter-Agency Agreement between NASA and the FAA which led to JPL's real-time GPS software development the FAA's GPS Wide Area Augmentation System (WAAS. He also led a group which is responsible for the quick-look GPS-based precise (few cm) orbits for the Topex spacecraft. His efforts to develop innovative new radio metric tracking technologies have resulted in 3 GPS-related patents recently submitted. He is recently was appointed the section manager for JPL's Tracking Systems and Applications Section.

Ronald Muellerschoen received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. He is currently a Member of the Technical Staff in the Earth Orbiter Systems Group at the Jet Propulsion Laboratory (JPL). His work at JPL has concentrated on the development of efficient filtering/smoothing software for processing GPS data and development of wide area differential systems.

Timothy Munson received his BS in Engineering from Virginia Polytechnic Institute & State University in 1981. He joined the technical staff at JPL in the GPS Systems Group in 1984. He currently does system engineering for GPS flight receivers in the software and hardware areas.

Donovan Spitzmesser received his B.A. degree in Mathematics from California State University, Los Angeles in 1972. He joined the Technical Staff at JPL in 1969 and has been designing RF Systems for GPS receivers since 1978.

Jeffrey Tien received his B.S. degree in Electrical Engineering with honors from California Polytechnic University, Pomona, in 1990 and his M.S. degree in Electrical Engineering from University of Southern

California in 1993. He joined JPL as a Member of the Technical Staff in the GPS Systems Group in 1990. His work at JPL has mainly been focused on the hardware aspect of the advanced GPS receiver development.

Sien-Chong Wu is currently a Technical Group Leader in the Tracking Systems and Applications Section at JPL. He has been involved with the development of various tracking systems for deep space as well as near-Earth space vehicles, and their applications to precision geodesy. His current interest is in the area of real-time wide-area differential GPS and special applications of GPS technologies. Sien received his Ph.D. degree from the University of Waterloo, Ontario, Canada.

Larry Young received a B.A. degree in Physics from Johns Hopkins U. in 1970, and a Ph.D. in Nuclear Physics from SUNY at Stony Brook in 1975. He supervises the GPS Systems Group at JPL, and has worked on high-accuracy development of GPS measurement systems for the last eighteen years.

ABSTRACT

In February 1998 the Student Nitric Oxide Explorer (SNOE) was successfully launched and began scientific observations. In addition to three instruments designed by the University of Colorado's Laboratory of Atmospheric and Space Physics to study Nitric Oxide in the atmosphere, the spacecraft also carried a 600 gram GPS receiver designed and built by the Jet Propulsion Laboratory.

This receiver, known as microGPS, is a combination of simple low-power hardware and portable, efficient software that has been developed by JPL for spacecraft navigation in Earth orbit. It is intended for micro- and nano-satellite applications where mass and power budget margins are especially limited or as a robust second string to a conventional GPS receiver onboard any satellite.

The microGPS hardware consists of lightweight antenna/receiver electronics that acquire occasional samples of GPS signals while consuming an average power of less than 100 milliwatts. Peak power is 875 milliwatts. The samples are stored in the microGPS for subsequent processing. Because it employs a sparse sampling technique, the microGPS has applications in tumbling/spinning satellites for routine navigation as well as in safe-hold recovery for any satellite whose orientation is unknown.

In order to offer maximum flexibility in satellite design, the microGPS orbit determination software is designed for execution either onboard the spacecraft or on the ground. In the latter case, which was employed for the SNOE mission, the sparse GPS samples are telemetered to the ground and processed in post real-time to produce spacecraft orbits that can be uploaded to the satellite and projected ahead for real-time use. Onboard the spacecraft, the software could execute in the flight computer or in a special-purpose processor within the microGPS hardware unit (with slight increases in mass and power consumption).

This paper will describe on-orbit operational experience with the microGPS receiver on the SNOE spacecraft as well as preview the next generation, dual-frequency microGPS receiver to be launched in mid 1999 on STRV-1c, a geostationary transfer orbit spacecraft. Comparisons will be made between expected performance of the microGPS and actual observations. The design, expected and actual performance of the orbit determination software, which is rooted in the techniques and algorithms pioneered in JPL's high accuracy GIPSY/OASIS II software, will also be described.

INTRODUCTION

GPS measurements can provide precise positioning for users on earth and in earth orbits. Positioning to 1-cm accuracy has been reported for users on earth (Refs. 1, 2), and 2 cm for a user in a low earth orbit (Refs. 3, 4). Such high-precision positioning requires a state-of-the-art GPS receiver onboard to acquire precise GPS carrier phase and/or pseudorange data, to be processed with ground data from a network of tracking sites over a period of time. Such full-blown onboard receivers are not only costly, but also heavy and power hungry.

Many NASA, military and commercial satellite programs have a need for tracking systems with ultra-low power, mass and cost for medium accuracy (few hundred meters) orbit determination of small, low-earth orbiting satellites. Jet Propulsion Laboratory (JPL) and Colorado Center for Atmospheric Research (CCAR) have collaborated to develop a tracking system using a novel GPS technology, to be called microGPS.

Two missions have carried or will carry a microGPS receiver. The first, SNOE (Student Nitric Oxide Explorer), a student-built spacecraft developed by the University of Colorado's Laboratory of Atmospheric and Space Physics (LASP), was successfully launched in February, 1998 (Ref. 5). Although primarily an atmospheric science mission, it also carried the first flight microGPS into a 550 km, sun-synchronous circular orbit. The goal of the GPS experiment was orbit determination with at least 200 meter accuracy. The second mission is the STRV-1c (Space Technology Research Vehicle) being developed by the Defence and Evaluation Research Agency (DERA) in the United Kingdom (Ref. 6). Designed to be a new technology demonstrator, STRV-1c will be launched in late 1999 into a geostationary transfer orbit (GTO). From this highly elliptical orbit, a second-generation microGPS will attempt to characterize the dual-frequency GPS signal strength from 300 km to geosynchronous orbit altitudes.

The onboard microGPS receiver is basically a "bit grabber", consisting of a GPS patch antenna, an inexpensive oscillator, a signal downconverter/sampler, and a memory chip. Such a receiver can fulfill stringent power (<0.1 W) and mass (<1 kg) constraints, and, with the inclusion of an onboard processor to execute detection and orbit determination software, could potentially offer autonomous tracking capability. The microGPS requires very low power because it awakes from a "sleep" mode only occasionally to sample GPS signals for a short duration.

Each GPS signal sample is processed by software which implements an acquisition and observable extraction algorithm developed at JPL specifically to process microGPS data. Implementation of GPS processing normally performed by highly parallel hardware on a single channel, sequential processor necessitated a specialized approach to making Doppler and pseudorange measurements with microGPS data. This approach reduced the required computation to search for GPS signals from Order (N^2) to Order (NlogN). The resulting observables are carrier Doppler and ambiguous pseudorange, the latter with an ambiguity of 1 millisecond (~300 km).

Among the challenges in orbit determination are the resolution of the pseudorange ambiguity, the determination of measurement timetag which, depending on clock stability, could drift off by up to one second between sparse measurement epochs, and the convergence of the orbit solution from a cold start with poor a priori knowledge of the orbit.

The processing procedure and the estimation scheme, as well as results of a simulation analysis have been reported earlier (Ref. 7). The results of a demonstration using actual space GPS data from the GPS/MET satellite has been reported in (Ref. 8). This paper reports the results of an assessment of early SNOE in-flight data quality and orbit accuracy. The Real-Time Gipsy (RTG) software system (Ref. 9) developed at JPL is used for the analysis. These results demonstrate the expected data quality, the robustness of the pseudorange ambiguity resolution software, and confirm the orbit accuracy predicted by pre-flight analysis.

BACKGROUND

This section provides a brief description on the microGPS receiver architecture, the SNOE mission specifics, observable extraction software, and the ambiguity resolution of GPS pseudorange data. A more detailed description of ambiguity resolution has been given in Ref. 7.

microGPS Flight Hardware

The microGPS flight receiver, an ultra-low mass and power flight receiver, was designed, built and flight qualified at JPL. The ultra-low mass of the microGPS receiver is partly attributable to a modified hardware/software architecture in which all GPS specific signal processing typically implemented in hardware has been moved to software (see Figure 1).

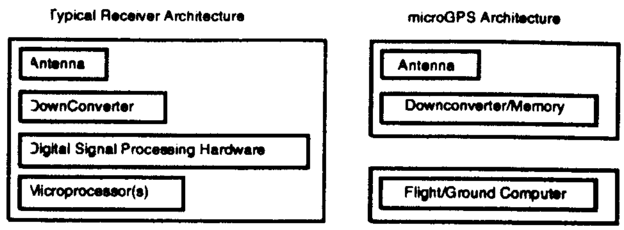

Figure 1. Receiver Architecture Comparison

In addition to power savings realized by this much simplified hardware configuration, the microGPS receiver consumes less power than typical flight GPS receivers because it uses a sparse sampling technique in which the receiver awakens and acquires GPS data only periodically, remaining "asleep" between samples. The microGPS acquires and stores short duration snapshots (typically a few milliseconds) of raw GPS signal at a programmable rate (typically a few times per orbit). In addition, individual snapshots can be single, short duration or bursts of samples whose number and sample spacing are also programmable.

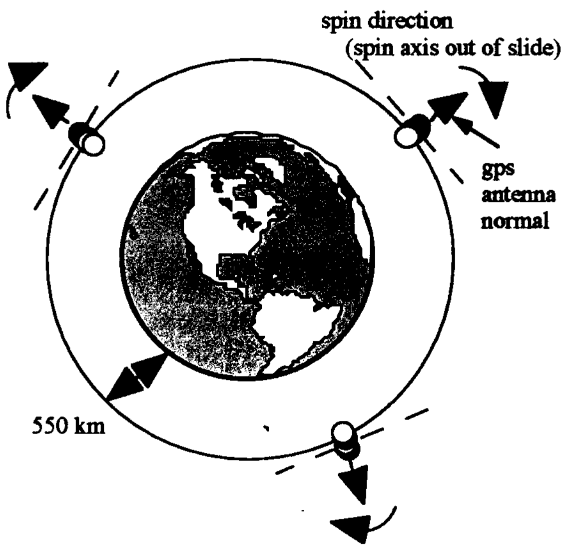

Figure 2. Simplified Spinning Satellite Configuration & Data Acquisition Scheme

The raw GPS signal samples are timetagged by the microGPS's real-time clock and then transferred to spacecraft flight computer. Once received by the flight computer, the GPS sample bits will be stored for later transmission to the ground and subsequent ground processing (as done for SNOE & planned for STRV) or processed in real or near-real time by onboard flight software. With proper processing software, these snapshots of the GPS constellation yield Doppler and pseudorange observables for all GPS satellites in view of the antenna which can produce moderately accurate orbits.

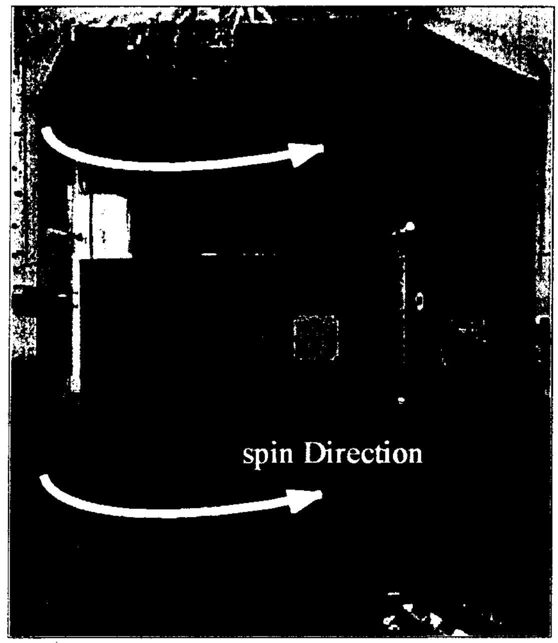

Figure 3. View of microGPS antenna/receiver after integration on the SNOE spacecraft.

SNOE Hardware Configuration & Data Acquisition

The SNOE spacecraft is a spinning satellite (~5 rpm) whose spin axis is perpendicular to the velocity vector as well as the nadir vector (i.e. rolls like a barrel). The GPS antenna was placed on the satellite such that its boresight was perpendicular to the spin axis (see Figures 2 & 3) and thus rotating with the spacecraft from nadir pointing to zenith pointing and back 5 time per minute. This configuration is ideal for a sparse sampling receiver and not very conducive to a continuously tracking receiver.

To minimize cost as well as impact on the SNOE mission, the microGPS was designed with the same custom, serial, flight computer interface as the three primary science instruments. It also was provided with the trigger signal from on-board horizon crossing sensor so that the GPS snapshots could be taken when the antenna boresight was near zenith pointing.

The microGPS receiver that was delivered to the SNOE project for satellite integration was approximately 5cm x 12cm x 12cm (see Figure 4). Including its integral patch antenna, mass is 595 grams. The power consumption is 75 milliwatts orbit average (in standby mode, ready for commands with oscillator warm) and 875 milliwatts peak (during data acquisition, which lasts less than 25 milliseconds).

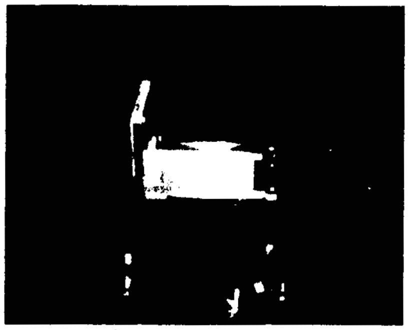

Figure 4. microGPS Receiver on Vibration Table

For the SNOE mission, the nominal data snapshot duration has been 20 milliseconds with samples acquired every 15 minutes (~4 times per orbit). The data volume is about 450 kilobytes per day. Based on preliminary orbit studies, the sampling time and the interval between samples could be reduced to 10 milliseconds and 30 minutes, respectively, reducing the daily data volume to ~100 kilobytes without loss of orbit accuracy.

Observable Extraction

The parallel nature of typical hardware-based GPS processing has permitted the implementation of Order (N^2) computations in Order (N) time using N parallel channels. To practically implement GPS signal search and observable measurement in software (using an inherently sequential computation engine), an ANSI-C++ set of classes were written to implement the Fourier-based technique of time-domain correlation (Ref. 10).

The basic algorithm for GPS signal search, acquisition and observable measurement operates on an input which consists of a timetagged sequence of sampled antenna data. These data are, in the case of microGPS, downconverted, filtered, single-bit quantized, digital bit streams. The receiver samples the signal at ~20 MBPS but can be programmed to perform a sum-and-dump filter and decimate function to reduce the data rate to ~2 MBPS (the latter is SNOE default operational mode). The sampled data are searched in Doppler (up to ±45 kHz) and in delay (over 1 repeat cycle of the Coarse-Acquisition (C/A) code, 1 millisecond). The search takes place for each satellite predicted to be visible at the time of capture (or all possible PRNs if the orbit and timetag offset are yet unknown).

Doppler space is searched sequentially with, at each Doppler point, the entire delay space searched in Order (NlogN) time. The time correlation of the sampled data with an appropriately formed model is accomplished by multiplying their Fourier transforms and inverse transforming the product back to the time domain, forming the full cross-correlation function which can be checked for amplitude as a function of delay or pseudorange. Both pseudorange and Doppler observables are interpolated from within the correlation function with peak amplitude (pseudorange) and between the peak correlation function and its two nearest Doppler neighbors (Doppler).

An important distinction between pseudorange produced with the microGPS and the usual GPS pseudorange observable should be made at this point. While the usual GPS receiver pseudorange represents absolute, unambiguous range (plus transmitter and receiver clock offsets), the microGPS can reliably produce only a 1 millisecond (300 km) pseudorange. This is due to the fact that 20 milliseconds of sampled data produced each epoch by microGPS is not sufficient either to decode the navigation data message (and thus GPS time is unavailable) or to reliably determine the location of the bit transitions of the navigation message. As will be outlined below, this deficiency is overcome by clever processing of ambiguous pseudorange along with Doppler measurements from multiple satellites.

The current version of observable extraction software executes on PowerMacintosh computers but will be ported to GPS-on-a-Chip receiver co-developed by JPL, Goddard Space Flight Center, and Stanford University (Ref. 11) for space flight applications.

On-orbit Receiver Performance

On-orbit performance of the SNOE microGPS hardware and observable extraction software is summarized in Table 1.

Mean GPS Satellites Detected per Snapshot	6.4
Mean SNR (C/N_0)	45.5 dBHz
Doppler Accuracy (1 sigma)	6.5 meters / second
Pseudorange Accuracy (1 sigma)	14 meters

Table 1. Summary statistics for 04/08/98

The Doppler and pseudorange measurement accuracy can be favorably compared with post-fit residual plots shown in Figure 8 & 10. Note that the pseudorange post-fit residual includes effects of SA. Figure 5 shows a plot of detected SNR versus measured Doppler for a typical day's worth of data. The skewing of the peak SNR towards positive Doppler can be explained by the value of the "trigger delay" parameter programmed into the microGPS on that particular day which resulted in the time of each snapshot occurring slight after the GPS antenna was zenith pointing. At the actual capture moment the antenna boresight was pointed slight forward, towards the velocity vector and the gain pattern was thus peaked at satellites with slightly positive Doppler shifts.

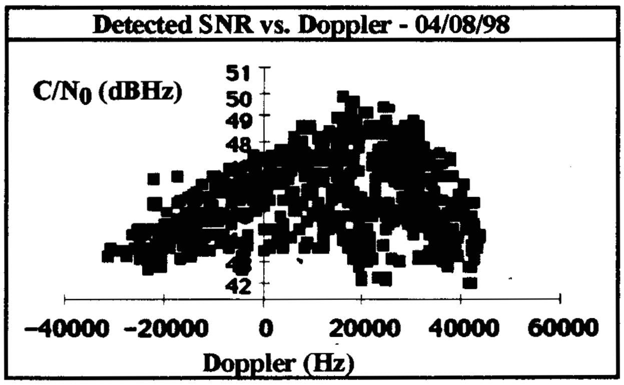

Figure 5. Signal-to-Noise Ratio vs. Doppler Plot of all GPS satellites detected during 04/08/98

Ambiguity Resolution of GPS Pseudorange Data

The sparse sampling technique used in the microGPS receiver precludes the acquisition of traditional GPS data types, namely, carrier phase and unambiguous pseudorange. Instead, the data types available are carrier Doppler and ambiguous pseudorange with an ambiguity of 1 ms (~300 km or the C/A code repeat period). These data types, acquired at a few time points, are not sufficient for orbit determination even at the kilometer level. However, the pseudorange ambiguity can be resolved with the help of the Doppler data, promoting the ambiguous pseudorange into a far stronger data type.

The resolution of pseudorange ambiguity is done in two steps. First, a crude orbit solution accurate to better than 50 km is determined with the Doppler data. Next, an unambiguous pseudorange data set is computed based on this crude orbit and the known (to a far better accuracy) GPS orbits. The accuracy of these computed pseudorange measurements, which is better than 50 km, is well within the 300-km pseudorange ambiguity. This facilitates the resolution simply by direct comparison of these computed pseudorange measurements and the actual ambiguous pseudorange measurements. The process has been described in detail in Ref. 5.

THE RTG SOFTWARE SYSTEM

The simulation analysis reported in Ref. 7 was performed using the GIPSY/OASIS II software set (Ref. 11) developed in an epoch-state filtering architecture which is not ideal for real time applications or for use by an onboard computer. A new software set, the Real-Time Gipsy (RTG), has been developed at JPL (Ref. 9).

RTG is written in ANSI-C and is capable of processing general radio-metric data types in real time on an onboard processor. RTG is also currently in use for the FAA's real-time GPS Wide-Area Augmentation System (WAAS). It is near its completion and is capable of processing microGPS data types as well as the usual GPS data types (phase and pseudorange).

A numerical integrator is used to allow arbitrary extension of the dynamic models. A current-state, general process-noise UD factorized filter (Ref. 12) is implemented in RTG.

Currently, RTG executes on HP workstations under UNIX, and on PCs. Its target platforms for the SNOE and STRV missions are ground based PowerPC Macintosh and HP9000 workstations. The software has been written in such a way that eventual migration to a real-time, flight processor will be straightforward.

ORBIT RESULTS FROM SNOE IN-FLIGHT DATA

We have investigated a few segments of SNOE data acquired during the first few week of its flight. The timetable of the investigated data segments is as shown in Figure 6. The first data segment, acquired on March 04, 1998 at variable intervals for a period of 2.3 hours, was used as software robustness test. The second data segment, acquired on March 29, at a 16-minute interval over a period of 2.7 hours, was used as data quality assessment. The third data segment covers a continuous 2.4-day period on April 07–09, also at the 16-minute interval. Only this long data segment was used for orbit quality assessment.

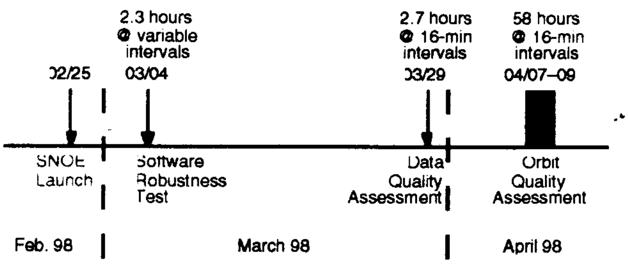

Figure 6. Early SNOE flight data segments

Software robustness test

The software robustness that needs to be demonstrated is its ability to resolve the pseudorange ambiguities. For this test, we investigate the 10 epochs of data separated at 102 seconds on March 04. In particular, the ambiguous pseudorange residuals, after removing integer milli-seconds, as determined by fitting to the Doppler inferred SNOE orbit, were investigated. The key factor for the ambiguity resolution is the clustering of the 6 or 7 measurement residuals at each epoch. Any data residual with a deviation greater than about 0.2 times the millisecond ambiguity from the cluster mean is labeled as outlier and discarded. Fifty-nine out of the 62 data residuals satisfy this criterion. Only two are labeled as outliers and one nearly so, labeled as "??" in Figure 7. The clustering of the remaining data residuals is very good (better than 0.06 millisecond) in general. It should be noted that, after discovering these pseudorange outliers, the observable extraction software was improved to detect and measure pseudorange with higher fidelity. Since then "outliers" have been virtually non-existent.

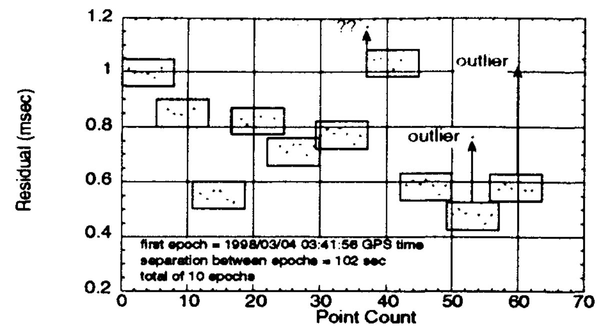

Figure 7. Ambiguous pseudorange residuals (integer millisecond removed) as fitted to Doppler inferred orbit

Data quality assessment

Examining the post-fit residuals of each data type assesses the data quality. Three classes of post-fit residuals are assessed. First, the Doppler residuals are computed using the best-fit Doppler inferred SNOE orbit. For the March 29 data segment, the Doppler residuals have an RMS value of 6.8 m/sec, as shown in Figure 8, in agreement with the expected data-noise error.

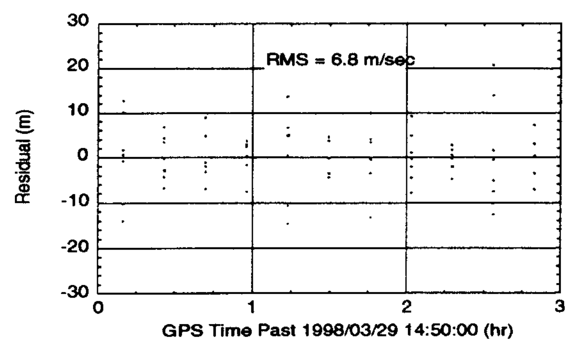

Figure 8. Post-fit Doppler residuals

Next, the residuals of the ambiguity resolved pseudorange data as fitted to the same Doppler inferred orbit are examined. Due to the drift in SNOE onboard clock, the data residuals are independently examined at each epoch. The pseudorange residuals as shown in Figure 9 have an RMS value of 25.8 µsec. While this RMS residual does not reflect the pseudorange data quality because of the large errors in the Doppler orbit, it provides another assessment as to how well the pseudorange ambiguities had been properly resolved.

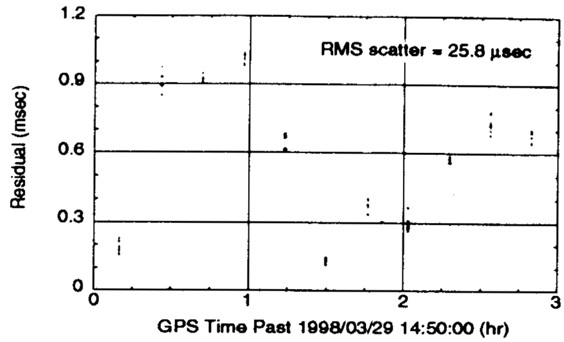

Figure 9. Ambiguity resolved pseudorange residuals as fitted to Doppler inferred orbit

The quality of the ambiguity resolved pseudorange data is assessed by the post-fit residuals derived using the best-fit pseudorange inferred SNOE orbit and white-noise clock solutions. The residuals have an RMS value of 47.4 m, as shown in Figure 10. Note that the effects of GPS Selective Availability (SA) clock dithering is of the order of 30 m; the actual pseudorange data quality is believed to be of the order of 30 m, somewhat larger than predicted by system noise alone. This deviation is not understood at this time, but would include contributions by multipath.

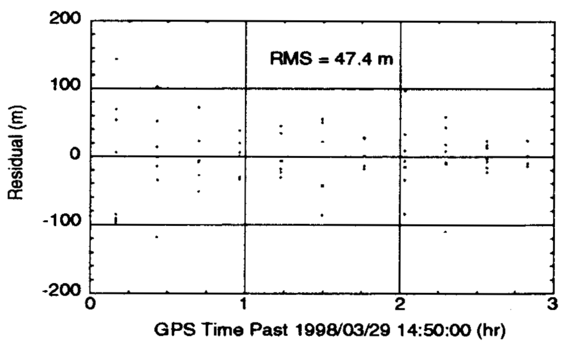

Figure 10. Post-fit pseudorange residuals

Orbit quality assessment

The long data segment on April 07–09 are processed, one day at a time, to derive independent SNOE orbit solutions. The orbit quality is assessed by propagating the first day solution into the second day and compared with the second-day solutions using different number of data epochs. In particular, the comparison using 2 and 4 data epochs is shown in Figure 11. In general, the orbit is better than 100 m in all three components within the data span. The error increases when the orbit is predicted into the future, but is still below 300 m (mostly in-track) after 0.5 hour of prediction. A further comparison shows that a 1-day orbit solution has a prediction error of ~10 m/hr in radial, 100 m/hr in-track, and no cross-track degradation.

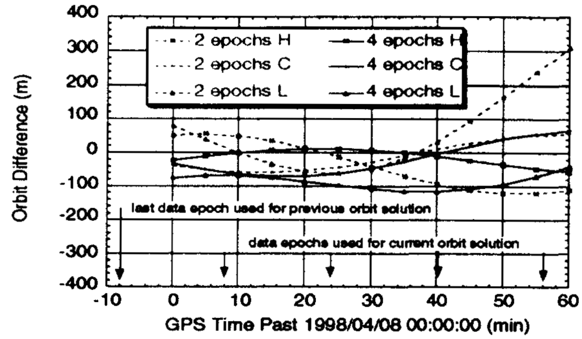

Figure 11. SNOE orbit difference from propagated previous-day solution (H—radial C—cross-track L—in-track)

Another assessment of the orbit solution is by examining the associating SNOE clock solutions. The clock was treated as a white-noise process to allow unconstrained variations. Figure 12 compares the clock solutions between two consecutive one-day data segments. The clock shows an apparent drift of 350 millisecond/day. The drift is continuous across the boundary of the two solution sets, implying consistent clock, and thus orbit, solutions.

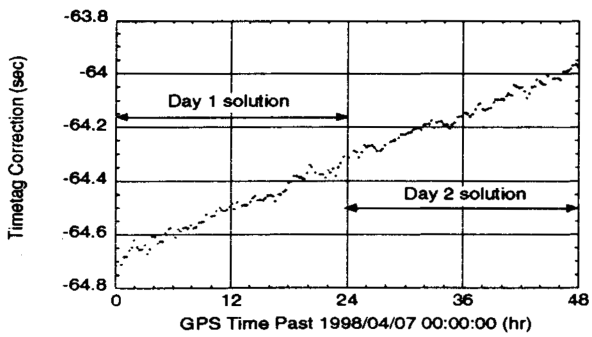

Figure 12. SNOE clock solution for two consecutive data segments

SUMMARY

The innovative microGPS architecture, a simplified flight receiver coupled with software designed to extract radiometric measurements and produce orbits, has been demonstrated to produce spacecraft orbits with ~75 meter accuracy. This performance is quite comparable to conventional GPS receivers that cost more, weigh more, and consume more power.

To accomplish this, a patent-pending algorithm was developed which can process Doppler + ambiguous pseudorange observables collected with widely spaced epochs (i.e. sparse sampling). In addition, a new, low-power, high-stability, multi-frequency RF downconverter was designed and space-qualified. These key advances led to a system which exceeded orbit accuracy goals by almost a factor of 3.

As previously mentioned, an enhanced, dual-frequency microGPS will fly aboard the STRV-1c spacecraft. While this will be the last JPL-built microGPS receivers, the functionality pioneered for SNOE will become a standard feature of the new, high precision GPS-based science instrument known as GPS-On-A-Chip (GOAC) (Ref. 13). As part of that instrument, the microGPS function will serve as a high reliability backup to the commercial technology used for GOAC. In addition, it may be used for attitude recovery during "tip-off" or initial satellite separation from the launch vehicle.

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REFERENCES

1. T. P. Yunck, S. C. Wu, J. T. Wu and C. L. Thornton, "Precise Tracking of Remote Sensing Satellites with the Global Positioning System," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 28, No. 1, Jan. 1990, pp. 108–116.

2. Heflin, MD, D. Jefferson, Y. Vigue, F. Webb, J. Zumberge and G. Blewitt, *Site Coordinates and Velocities from the Jet Propulsion Laboratory Using GPS*, SSMC(JPL) 94 P 01, IERS Tech. Note 17, 49, 1994.

3. T. P. Yunck, W. I. Bertiger, S. C. Wu, Y. E. Bar-Sever, E. J. Christensen, B. J. Haines, S. M. Lichten, R. J. Muellerschoen, Y. Vigue and P. Willis, "First assessment of GPS-based reduced dynamic orbit determination on TOPEX/ POSEIDON," *Geophys. Res. Lett.*, Vol. 21, No. 7, 1994, pp. 541-544.

4. W. I. Bertiger, Y. E. Bar-Sever, E. J. Christensen, E. S. Davis, J. R. Guinn, B. J. Haines, R. W. Ibanez-Meier, J. R. Jee, S. M. Lichten, W. G. Melbourne, R. J. Muellerschoen, T. N. Munson, Y. Vigue, S. C. Wu, T. P. Yunck, B. E. Schutz, P. A. M. Abusali, H. J. Rim, M. M. Watkins and P. Willis, "GPS Precise Tracking of Topex/Poseidon: Results and Implications," *J. Geophys. Res.* Vol. 99, No. C12, Dec., 1994, pp. 24449–24464.

5. S. Solomon et al., "The SNOE Spacecraft, Integration, Test, Launch, Operation and On-orbit Performance", Proc. 12th AIAA/USU Conference on Small Satellites, SSC98-IV-3, 1998.

6. R.J. Blott, N.S. Wells, J. Eves, "The STRV1 Microsatellite Series: Exploiting the geosynchronous transfer orbit", IAF Conference, 1997.

7. S. C. Wu, W. Bertiger, J. Srinivasan and A. Reichert, "MicorGPS for Orbit Determination of Earth Satellites," ION National Technical Meeting, Santa Monica, CA, Jan., 1996.

8. S. C. Wu, D. Kuang, S. M. Lichten, S. Nandi, L. J. Romans and J. M. Srinivasan, "Demonstration of MicroGPS for Low-Cost Orbit Determination,," AAS/AIAA Astrodynamics Specialist Conf., Sun Valley, ID, Aug. 1998.

9. W. I. Bertiger, Y. E. Bar-Sever, B. J. Haines, B. A. Iijima, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, R. J. Muellerschoen, T. N. Munson, A. W. Moore, L. J. Romans, B. D. Wilson, S. C. Wu, T. P. Yunck, G. Piesinger, and M. Whitehead, "A Prototype Real-Time Wide Area Differential GPS System," ION National Technical Meeting, Santa Monica, CA, Jan., 1997.

10. W. T. Cathey, *Optical Information Processing and Holography*, Wily-Interscience, NY, NY, 1974.

11. F. B. Webb and J. F. Zumberge, (ed.), *An Introduction to GIPSY/OASIS II*, JPL Internal Document D-11088, July 1993.

12. G. J. Bierman, *Factorization Methods for Discrete Sequential Estimation*, Academic Press, NY, NY, 1977.

13. T. K. Meehan et al., ""GPS-On-A-Chip" – An Advanced GPS Receiver for Spacecraft", To Be Presented at ION GPS-98, Nashville, TN, September 1998.

microGPS: On-orbit Demonstration of a New Approach to GPS for Space Applications

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BIOGRAPHY

Jeffrey Srinivasan received his B.A. degree in Engineering and Applied Sciences with honors from Harvard College in 1983 and his M.S. degree in Electrical Engineering from University of Southern California in 1988. He joined the technical staff at JPL in 1983 and is currently a Technical Group Leader. He was instrumental in various hardware/software aspects of the microGPS development.

Yoaz Bar-Sever received his Ph.D. in Applied Mathematics from the Technion - Israel Institute of technology, in 1987. From 1987 to 1989 he was a post-doctoral fellow at the Department of Applied Mathematics at Caltech. In 1993 he received an additional Master degree in Electrical Engineering from the University of Southern California. He joined JPL in 1989 where he has been involved in GPS technology development and its geophysical applications. He now supervises the Earth Orbiter Systems Group at JPL.

Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at JPL as a Member of the Technical Staff in the Earth Orbiter Systems Group. His work at JPL has been focused on the use of GPS, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems.

Stephen M. Lichten received a B.A. from Harvard in 1978 and a Ph.D. from Caltech in 1983. He then joined the Jet Propulsion Laboratory (JPL) in 1983, initially working on very long baseline interferometry and precision GPS orbit determination. In 1996, he helped develop the Inter-Agency Agreement between NASA and the FAA which led to JPL's real-time GPS software development the FAA's GPS Wide Area Augmentation System (WAAS. He also led a group which is responsible for the quick-look GPS-based precise (few cm) orbits for the Topex spacecraft. His efforts to develop innovative new radio metric tracking technologies have resulted in 3 GPS-related patents recently submitted. He is recently was appointed the section manager for JPL's Tracking Systems and Applications Section.

Ronald Muellerschoen received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. He is currently a Member of the Technical Staff in the Earth Orbiter Systems Group at the Jet Propulsion Laboratory (JPL). His work at JPL has concentrated on the development of efficient filtering/smoothing software for processing GPS data and development of wide area differential systems.

Timothy Munson received his BS in Engineering from Virginia Polytechnic Institute & State University in 1981. He joined the technical staff at JPL in the GPS Systems Group in 1984. He currently does system engineering for GPS flight receivers in the software and hardware areas.

Donovan Spitzmesser received his B.A. degree in Mathematics from California State University, Los Angeles in 1972. He joined the Technical Staff at JPL in 1969 and has been designing RF Systems for GPS receivers since 1978.

Jeffrey Tien received his B.S. degree in Electrical Engineering with honors from California Polytechnic University, Pomona, in 1990 and his M.S. degree in Electrical Engineering from University of Southern

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Sien-Chong Wu is currently a Technical Group Leader in the Tracking Systems and Applications Section at JPL. He has been involved with the development of various tracking systems for deep space as well as near-Earth space vehicles, and their applications to precision geodesy. His current interest is in the area of real-time wide-area differential GPS and special applications of GPS technologies. Sien received his Ph.D. degree from the University of Waterloo, Ontario, Canada.

Larry Young received a B.A. degree in Physics from Johns Hopkins U. in 1970, and a Ph.D. in Nuclear Physics from SUNY at Stony Brook in 1975. He supervises the GPS Systems Group at JPL, and has worked on high-accuracy development of GPS measurement systems for the last eighteen years.

ABSTRACT

In February 1998 the Student Nitric Oxide Explorer (SNOE) was successfully launched and began scientific observations. In addition to three instruments designed by the University of Colorado's Laboratory of Atmospheric and Space Physics to study Nitric Oxide in the atmosphere, the spacecraft also carried a 600 gram GPS receiver designed and built by the Jet Propulsion Laboratory.

This receiver, known as microGPS, is a combination of simple low-power hardware and portable, efficient software that has been developed by JPL for spacecraft navigation in Earth orbit. It is intended for micro- and nano-satellite applications where mass and power budget margins are especially limited or as a robust second string to a conventional GPS receiver onboard any satellite.

The microGPS hardware consists of lightweight antenna/receiver electronics that acquire occasional samples of GPS signals while consuming an average power of less than 100 milliwatts. Peak power is 875 milliwatts. The samples are stored in the microGPS for subsequent processing. Because it employs a sparse sampling technique, the microGPS has applications in tumbling/spinning satellites for routine navigation as well as in safe-hold recovery for any satellite whose orientation is unknown.

In order to offer maximum flexibility in satellite design, the microGPS orbit determination software is designed for execution either onboard the spacecraft or on the ground. In the latter case, which was employed for the SNOE mission, the sparse GPS samples are telemetered to the ground and processed in post real-time to produce spacecraft orbits that can be uploaded to the satellite and projected ahead for real-time use. Onboard the spacecraft, the software could execute in the flight computer or in a special-purpose processor within the microGPS hardware unit (with slight increases in mass and power consumption).

This paper will describe on-orbit operational experience with the microGPS receiver on the SNOE spacecraft as well as preview the next generation, dual-frequency microGPS receiver to be launched in mid 1999 on STRV-1c, a geostationary transfer orbit spacecraft. Comparisons will be made between expected performance of the microGPS and actual observations. The design, expected and actual performance of the orbit determination software, which is rooted in the techniques and algorithms pioneered in JPL's high accuracy GIPSY/OASIS II software, will also be described.

INTRODUCTION

GPS measurements can provide precise positioning for users on earth and in earth orbits. Positioning to 1-cm accuracy has been reported for users on earth (Refs. 1, 2), and 2 cm for a user in a low earth orbit (Refs. 3, 4). Such high-precision positioning requires a state-of-the-art GPS receiver onboard to acquire precise GPS carrier phase and/or pseudorange data, to be processed with ground data from a network of tracking sites over a period of time. Such full-blown onboard receivers are not only costly, but also heavy and power hungry.

Many NASA, military and commercial satellite programs have a need for tracking systems with ultra-low power, mass and cost for medium accuracy (few hundred meters) orbit determination of small, low-earth orbiting satellites. Jet Propulsion Laboratory (JPL) and Colorado Center for Atmospheric Research (CCAR) have collaborated to develop a tracking system using a novel GPS technology, to be called microGPS.

Two missions have carried or will carry a microGPS receiver. The first, SNOE (Student Nitric Oxide Explorer), a student-built spacecraft developed by the University of Colorado's Laboratory of Atmospheric and Space Physics (LASP), was successfully launched in February, 1998 (Ref. 5). Although primarily an atmospheric science mission, it also carried the first flight microGPS into a 550 km, sun-synchronous circular orbit. The goal of the GPS experiment was orbit determination with at least 200 meter accuracy. The second mission is the STRV-1c (Space Technology Research Vehicle) being developed by the Defence and Evaluation Research Agency (DERA) in the United Kingdom (Ref. 6). Designed to be a new technology demonstrator, STRV-1c will be launched in late 1999 into a geostationary transfer orbit (GTO). From this highly elliptical orbit, a second-generation microGPS will attempt to characterize the dual-frequency GPS signal strength from 300 km to geosynchronous orbit altitudes.

The onboard microGPS receiver is basically a "bit grabber", consisting of a GPS patch antenna, an inexpensive oscillator, a signal downconverter/sampler, and a memory chip. Such a receiver can fulfill stringent power (<0.1 W) and mass (<1 kg) constraints, and, with the inclusion of an onboard processor to execute detection and orbit determination software, could potentially offer autonomous tracking capability. The microGPS requires very low power because it awakes from a "sleep" mode only occasionally to sample GPS signals for a short duration.

Each GPS signal sample is processed by software which implements an acquisition and observable extraction algorithm developed at JPL specifically to process microGPS data. Implementation of GPS processing normally performed by highly parallel hardware on a single channel, sequential processor necessitated a specialized approach to making Doppler and pseudorange measurements with microGPS data. This approach reduced the required computation to search for GPS signals from Order (N^2) to Order (NlogN). The resulting observables are carrier Doppler and ambiguous pseudorange, the latter with an ambiguity of 1 millisecond (~300 km).

Among the challenges in orbit determination are the resolution of the pseudorange ambiguity, the determination of measurement timetag which, depending on clock stability, could drift off by up to one second between sparse measurement epochs, and the convergence of the orbit solution from a cold start with poor a priori knowledge of the orbit.

The processing procedure and the estimation scheme, as well as results of a simulation analysis have been reported earlier (Ref. 7). The results of a demonstration using actual space GPS data from the GPS/MET satellite has been reported in (Ref. 8). This paper reports the results of an assessment of early SNOE in-flight data quality and orbit accuracy. The Real-Time Gipsy (RTG) software system (Ref. 9) developed at JPL is used for the analysis. These results demonstrate the expected data quality, the robustness of the pseudorange ambiguity resolution software, and confirm the orbit accuracy predicted by pre-flight analysis.

BACKGROUND

This section provides a brief description on the microGPS receiver architecture, the SNOE mission specifics, observable extraction software, and the ambiguity resolution of GPS pseudorange data. A more detailed description of ambiguity resolution has been given in Ref. 7.

microGPS Flight Hardware

The microGPS flight receiver, an ultra-low mass and power flight receiver, was designed, built and flight qualified at JPL. The ultra-low mass of the microGPS receiver is partly attributable to a modified hardware/software architecture in which all GPS specific signal processing typically implemented in hardware has been moved to software (see Figure 1).

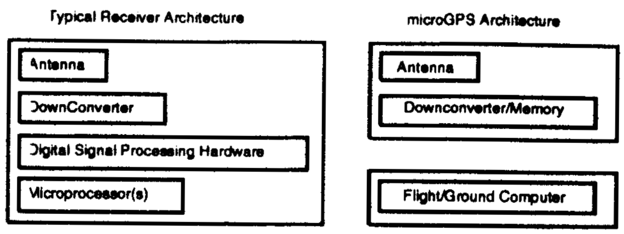

Figure 1. Receiver Architecture Comparison

In addition to power savings realized by this much simplified hardware configuration, the microGPS receiver consumes less power than typical flight GPS receivers because it uses a sparse sampling technique in which the receiver awakens and acquires GPS data only periodically, remaining "asleep" between samples. The microGPS acquires and stores short duration snapshots (typically a few milliseconds) of raw GPS signal at a programmable rate (typically a few times per orbit). In addition, individual snapshots can be single, short duration or bursts of samples whose number and sample spacing are also programmable.

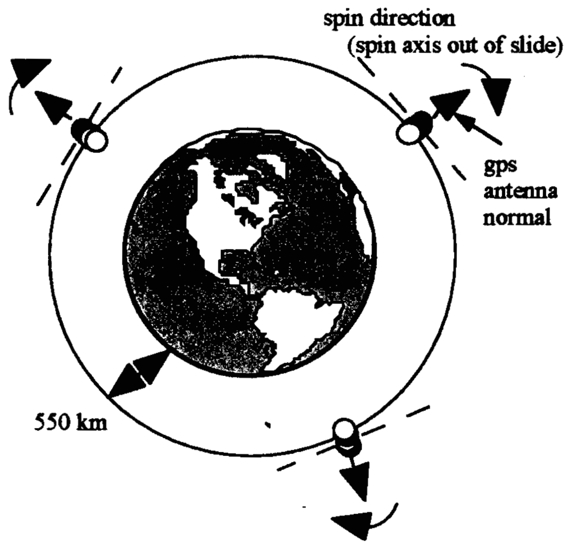

Figure 2. Simplified Spinning Satellite Configuration & Data Acquisition Scheme

The raw GPS signal samples are timetagged by the microGPS's real-time clock and then transferred to spacecraft flight computer. Once received by the flight computer, the GPS sample bits will be stored for later transmission to the ground and subsequent ground processing (as done for SNOE & planned for STRV) or processed in real or near-real time by onboard flight software. With proper processing software, these snapshots of the GPS constellation yield Doppler and pseudorange observables for all GPS satellites in view of the antenna which can produce moderately accurate orbits.

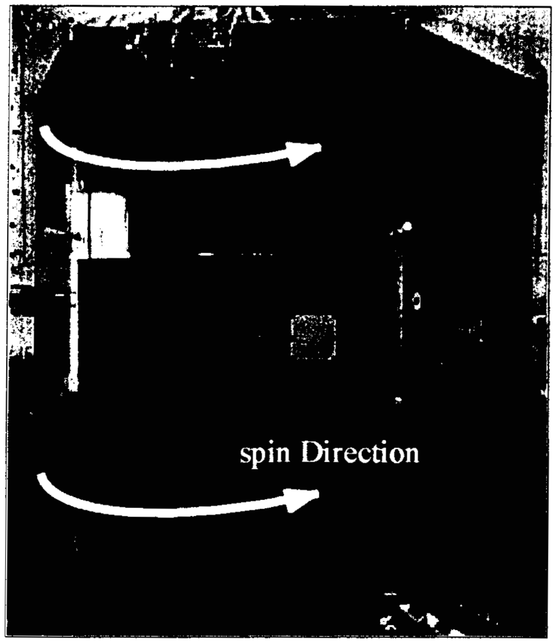

Figure 3. View of microGPS antenna/receiver after integration on the SNOE spacecraft.

SNOE Hardware Configuration & Data Acquisition

The SNOE spacecraft is a spinning satellite (~5 rpm) whose spin axis is perpendicular to the velocity vector as well as the nadir vector (i.e. rolls like a barrel). The GPS antenna was placed on the satellite such that its boresight was perpendicular to the spin axis (see Figures 2 & 3) and thus rotating with the spacecraft from nadir pointing to zenith pointing and back 5 time per minute. This configuration is ideal for a sparse sampling receiver and not very conducive to a continuously tracking receiver.

To minimize cost as well as impact on the SNOE mission, the microGPS was designed with the same custom, serial, flight computer interface as the three primary science instruments. It also was provided with the trigger signal from on-board horizon crossing sensor so that the GPS snapshots could be taken when the antenna boresight was near zenith pointing.

The microGPS receiver that was delivered to the SNOE project for satellite integration was approximately 5cm x 12cm x 12cm (see Figure 4). Including its integral patch antenna, mass is 595 grams. The power consumption is 75 milliwatts orbit average (in standby mode, ready for commands with oscillator warm) and 875 milliwatts peak (during data acquisition, which lasts less than 25 milliseconds).

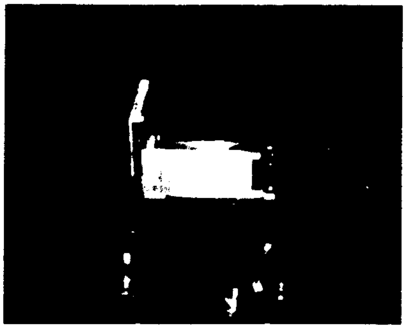

Figure 4. microGPS Receiver on Vibration Table

For the SNOE mission, the nominal data snapshot duration has been 20 milliseconds with samples acquired every 15 minutes (~4 times per orbit). The data volume is about 450 kilobytes per day. Based on preliminary orbit studies, the sampling time and the interval between samples could be reduced to 10 milliseconds and 30 minutes, respectively, reducing the daily data volume to ~100 kilobytes without loss of orbit accuracy.

Observable Extraction

The parallel nature of typical hardware-based GPS processing has permitted the implementation of Order (N^2) computations in Order (N) time using N parallel channels. To practically implement GPS signal search and observable measurement in software (using an inherently sequential computation engine), an ANSI-C++ set of classes were written to implement the Fourier-based technique of time-domain correlation (Ref. 10).

The basic algorithm for GPS signal search, acquisition and observable measurement operates on an input which consists of a timetagged sequence of sampled antenna data. These data are, in the case of microGPS, downconverted, filtered, single-bit quantized, digital bit streams. The receiver samples the signal at ~20 MBPS but can be programmed to perform a sum-and-dump filter and decimate function to reduce the data rate to ~2 MBPS (the latter is SNOE default operational mode). The sampled data are searched in Doppler (up to ±45 kHz) and in delay (over 1 repeat cycle of the Coarse-Acquisition (C/A) code, 1 millisecond). The search takes place for each satellite predicted to be visible at the time of capture (or all possible PRNs if the orbit and timetag offset are yet unknown).

Doppler space is searched sequentially with, at each Doppler point, the entire delay space searched in Order (NlogN) time. The time correlation of the sampled data with an appropriately formed model is accomplished by multiplying their Fourier transforms and inverse transforming the product back to the time domain, forming the full cross-correlation function which can be checked for amplitude as a function of delay or pseudorange. Both pseudorange and Doppler observables are interpolated from within the correlation function with peak amplitude (pseudorange) and between the peak correlation function and its two nearest Doppler neighbors (Doppler).

An important distinction between pseudorange produced with the microGPS and the usual GPS pseudorange observable should be made at this point. While the usual GPS receiver pseudorange represents absolute, unambiguous range (plus transmitter and receiver clock offsets), the microGPS can reliably produce only a 1 millisecond (300 km) pseudorange. This is due to the fact that 20 milliseconds of sampled data produced each epoch by microGPS is not sufficient either to decode the navigation data message (and thus GPS time is unavailable) or to reliably determine the location of the bit transitions of the navigation message. As will be outlined below, this deficiency is overcome by clever processing of ambiguous pseudorange along with Doppler measurements from multiple satellites.

The current version of observable extraction software executes on PowerMacintosh computers but will be ported to GPS-on-a-Chip receiver co-developed by JPL, Goddard Space Flight Center, and Stanford University (Ref. 11) for space flight applications.

On-orbit Receiver Performance

On-orbit performance of the SNOE microGPS hardware and observable extraction software is summarized in Table 1.

Mean GPS Satellites Detected per Snapshot	6.4
Mean SNR (C/N_0)	45.5 dBHz
Doppler Accuracy (1 sigma)	6.5 meters / second
Pseudorange Accuracy (1 sigma)	14 meters

Table 1. Summary statistics for 04/08/98

The Doppler and pseudorange measurement accuracy can be favorably compared with post-fit residual plots shown in Figure 8 & 10. Note that the pseudorange post-fit residual includes effects of SA. Figure 5 shows a plot of detected SNR versus measured Doppler for a typical day's worth of data. The skewing of the peak SNR towards positive Doppler can be explained by the value of the "trigger delay" parameter programmed into the microGPS on that particular day which resulted in the time of each snapshot occurring slight after the GPS antenna was zenith pointing. At the actual capture moment the antenna boresight was pointed slight forward, towards the velocity vector and the gain pattern was thus peaked at satellites with slightly positive Doppler shifts.

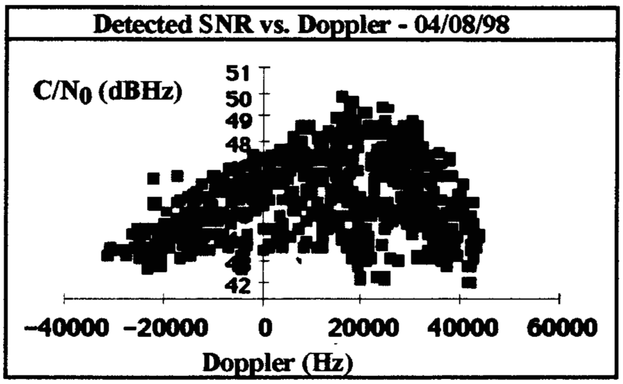

Figure 5. Signal-to-Noise Ratio vs. Doppler Plot of all GPS satellites detected during 04/08/98

Ambiguity Resolution of GPS Pseudorange Data

The sparse sampling technique used in the microGPS receiver precludes the acquisition of traditional GPS data types, namely, carrier phase and unambiguous pseudorange. Instead, the data types available are carrier Doppler and ambiguous pseudorange with an ambiguity of 1 ms (~300 km or the C/A code repeat period). These data types, acquired at a few time points, are not sufficient for orbit determination even at the kilometer level. However, the pseudorange ambiguity can be resolved with the help of the Doppler data, promoting the ambiguous pseudorange into a far stronger data type.

The resolution of pseudorange ambiguity is done in two steps. First, a crude orbit solution accurate to better than 50 km is determined with the Doppler data. Next, an unambiguous pseudorange data set is computed based on this crude orbit and the known (to a far better accuracy) GPS orbits. The accuracy of these computed pseudorange measurements, which is better than 50 km, is well within the 300-km pseudorange ambiguity. This facilitates the resolution simply by direct comparison of these computed pseudorange measurements and the actual ambiguous pseudorange measurements. The process has been described in detail in Ref. 5.

THE RTG SOFTWARE SYSTEM

The simulation analysis reported in Ref. 7 was performed using the GIPSY/OASIS II software set (Ref. 11) developed in an epoch-state filtering architecture which is not ideal for real time applications or for use by an onboard computer. A new software set, the Real-Time Gipsy (RTG), has been developed at JPL (Ref. 9).

RTG is written in ANSI-C and is capable of processing general radio-metric data types in real time on an onboard processor. RTG is also currently in use for the FAA's real-time GPS Wide-Area Augmentation System (WAAS). It is near its completion and is capable of processing microGPS data types as well as the usual GPS data types (phase and pseudorange).

A numerical integrator is used to allow arbitrary extension of the dynamic models. A current-state, general process-noise UD factorized filter (Ref. 12) is implemented in RTG.

Currently, RTG executes on HP workstations under UNIX, and on PCs. Its target platforms for the SNOE and STRV missions are ground based PowerPC Macintosh and HP9000 workstations. The software has been written in such a way that eventual migration to a real-time, flight processor will be straightforward.

ORBIT RESULTS FROM SNOE IN-FLIGHT DATA

We have investigated a few segments of SNOE data acquired during the first few week of its flight. The timetable of the investigated data segments is as shown in Figure 6. The first data segment, acquired on March 04, 1998 at variable intervals for a period of 2.3 hours, was used as software robustness test. The second data segment, acquired on March 29, at a 16-minute interval over a period of 2.7 hours, was used as data quality assessment. The third data segment covers a continuous 2.4-day period on April 07–09, also at the 16-minute interval. Only this long data segment was used for orbit quality assessment.

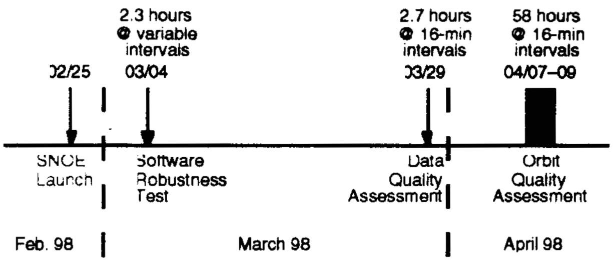

Figure 6. Early SNOE flight data segments

Software robustness test

The software robustness that needs to be demonstrated is its ability to resolve the pseudorange ambiguities. For this test, we investigate the 10 epochs of data separated at 102 seconds on March 04. In particular, the ambiguous pseudorange residuals, after removing integer milliseconds, as determined by fitting to the Doppler inferred SNOE orbit, were investigated. The key factor for the ambiguity resolution is the clustering of the 6 or 7 measurement residuals at each epoch. Any data residual with a deviation greater than about 0.2 times the millisecond ambiguity from the cluster mean is labeled as outlier and discarded. Fifty-nine out of the 62 data residuals satisfy this criterion. Only two are labeled as outliers and one nearly so, labeled as "??" in Figure 7. The clustering of the remaining data residuals is very good (better than 0.06 millisecond) in general. It should be noted that, after discovering these pseudorange outliers, the observable extraction software was improved to detect and measure pseudorange with higher fidelity. Since then "outliers" have been virtually non-existent.

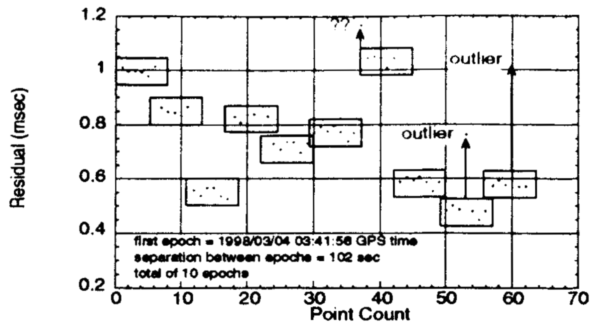

Figure 7. Ambiguous pseudorange residuals (integer millisecond removed) as fitted to Doppler inferred orbit

Data quality assessment

Examining the post-fit residuals of each data type assesses the data quality. Three classes of post-fit residuals are assessed. First, the Doppler residuals are computed using the best-fit Doppler inferred SNOE orbit. For the March 29 data segment, the Doppler residuals have an RMS value of 6.8 m/sec, as shown in Figure 8, in agreement with the expected data-noise error.

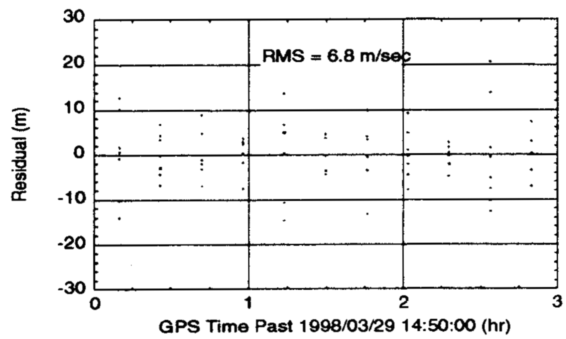

Figure 8. Post-fit Doppler residuals

Next, the residuals of the ambiguity resolved pseudorange data as fitted to the same Doppler inferred orbit are examined. Due to the drift in SNOE onboard clock, the data residuals are independently examined at each epoch. The pseudorange residuals as shown in Figure 9 have an RMS value of 25.8 μsec. While this RMS residual does not reflect the pseudorange data quality because of the large errors in the Doppler orbit, it provides another assessment as to how well the pseudorange ambiguities had been properly resolved.

To accomplish this, a patent-pending algorithm was developed which can process Doppler + ambiguous pseudorange observables collected with widely spaced epochs (i.e. sparse sampling). In addition, a new, low-power, high-stability, multi-frequency RF downconverter was designed and space-qualified. These key advances led to a system which exceeded orbit accuracy goals by almost a factor of 3.

As previously mentioned, an enhanced, dual-frequency microGPS will fly aboard the STRV-1c spacecraft. While this will be the last JPL-built microGPS receivers, the functionality pioneered for SNOE will become a standard feature of the new, high precision GPS-based science instrument known as GPS-On-A-Chip (GOAC) (Ref. 13). As part of that instrument, the microGPS function will serve as a high reliability backup to the commercial technology used for GOAC. In addition, it may be used for attitude recovery during "tip-off" or initial satellite separation from the launch vehicle.

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REFERENCES

1. T. P. Yunck, S. C. Wu, J. T. Wu and C. L. Thornton, "Precise Tracking of Remote Sensing Satellites with the Global Positioning System," *IEEE Trans. Geosci. and Remote Sensing*, Vol. 28, No. 1, Jan. 1990, pp. 108–116.

2. Heflin, MD, D. Jefferson, Y. Vigue, F. Webb, J. Zumberge and G. Blewitt, *Site Coordinates and Velocities from the Jet Propulsion Laboratory Using GPS*, SSMC(JPL) 94 P 01, IERS Tech. Note 17, 49, 1994.

3. T. P. Yunck, W. I. Bertiger, S. C. Wu, Y. E. Bar-Sever, E. J. Christensen, B. J. Haines, S. M. Lichten, R. J. Muellerschoen, Y. Vigue and P. Willis, "First assessment of GPS-based reduced dynamic orbit determination on TOPEX/ POSEIDON," *Geophys. Res. Lett.*, Vol. 21, No. 7, 1994, pp. 541-544.

4. W. I. Bertiger, Y. E. Bar-Sever, E. J. Christensen, E. S. Davis, J. R. Guinn, B. J. Haines, R. W. Ibanez-Meier, J. R. Jee, S. M. Lichten, W. G. Melbourne, R. J. Muellerschoen, T. N. Munson, Y. Vigue, S. C. Wu, T. P. Yunck, B. E. Schutz, P. A. M. Abusali, H. J. Rim, M. M. Watkins and P. Willis, "GPS Precise Tracking of Topex/Poseidon: Results and Implications," *J. Geophys. Res.* Vol. 99, No. C12, Dec., 1994, pp. 24449–24464.

5. S. Solomon et al., "The SNOE Spacecraft, Integration, Test, Launch, Operation and On-orbit Performance", Proc. 12th AIAA/USU Conference on Small Satellites, SSC98-IV-3, 1998.

6. R.J. Blott, N.S. Wells, J. Eves, "The STRV1 Microsatellite Series: Exploiting the geosynchronous transfer orbit", IAF Conference, 1997.

7. S. C. Wu, W. Bertiger, J. Srinivasan and A. Reichert, "MicorGPS for Orbit Determination of Earth Satellites," ION National Technical Meeting, Santa Monica, CA, Jan., 1996.

8. S. C. Wu, D. Kuang, S. M. Lichten, S. Nandi, L. J. Romans and J. M. Srinivasan, "Demonstration of MicroGPS for Low-Cost Orbit Determination,," AAS/AIAA Astrodynamics Specialist Conf., Sun Valley, ID, Aug. 1998.

9. W. I. Bertiger, Y. E. Bar-Sever, B. J. Haines, B. A. Iijima, S. M. Lichten, U. J. Lindqwister, A. J. Mannucci, R. J. Muellerschoen, T. N. Munson, A. W. Moore, L. J. Romans, B. D. Wilson, S. C. Wu, T. P. Yunck, G. Piesinger, and M. Whitehead, "A Prototype Real-Time Wide Area Differential GPS System," ION National Technical Meeting, Santa Monica, CA, Jan., 1997.

10. W. T. Cathey, *Optical Information Processing and Holography*, Wily-Interscience, NY, NY, 1974.

11. F. B. Webb and J. F. Zumberge, (ed.), *An Introduction to GIPSY/OASIS II*, JPL Internal Document D-11088, July 1993.

12. G. J. Bierman, *Factorization Methods for Discrete Sequential Estimation*, Academic Press, NY, NY, 1977.

13. T. K. Meehan et al., ""GPS-On-A-Chip" – An Advanced GPS Receiver for Spacecraft", To Be Presented at ION GPS-98, Nashville, TN, September 1998.

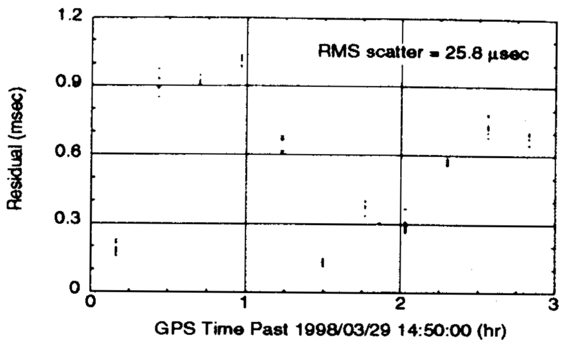

Figure 9. Ambiguity resolved pseudorange residuals as fitted to Doppler inferred orbit

The quality of the ambiguity resolved pseudorange data is assessed by the post-fit residuals derived using the best-fit pseudorange inferred SNOE orbit and white-noise clock solutions. The residuals have an RMS value of 47.4 m, as shown in Figure 10. Note that the effects of GPS Selective Availability (SA) clock dithering is of the order of 30 m; the actual pseudorange data quality is believed to be of the order of 30 m, somewhat larger than predicted by system noise alone. This deviation is not understood at this time, but would include contributions by multipath.

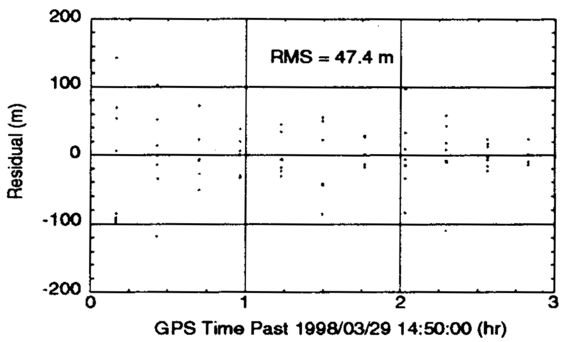

Figure 10. Post-fit pseudorange residuals

Orbit quality assessment

The long data segment on April 07–09 are processed, one day at a time, to derive independent SNOE orbit solutions. The orbit quality is assessed by propagating the first day solution into the second day and compared with the second-day solutions using different number of data epochs. In particular, the comparison using 2 and 4 data epochs is shown in Figure 11. In general, the orbit is better than 100 m in all three components within the data span. The error increases when the orbit is predicted into the future, but is still below 300 m (mostly in-track) after 0.5 hour of prediction. A further comparison shows that a 1-day orbit solution has a prediction error of ~10 m/hr in radial, 100 m/hr in-track, and no cross-track degradation.

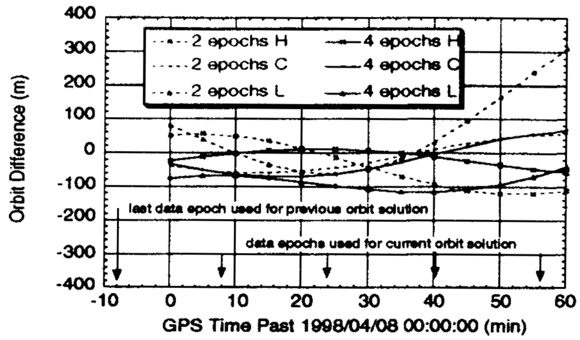

Figure 11. SNOE orbit difference from propagated previous-day solution (H—radial C—cross-track L—in-track)

Another assessment of the orbit solution is by examining the associating SNOE clock solutions. The clock was treated as a white-noise process to allow unconstrained variations. Figure 12 compares the clock solutions between two consecutive one-day data segments. The clock shows an apparent drift of 350 millisecond/day. The drift is continuous across the boundary of the two solution sets, implying consistent clock, and thus orbit, solutions.

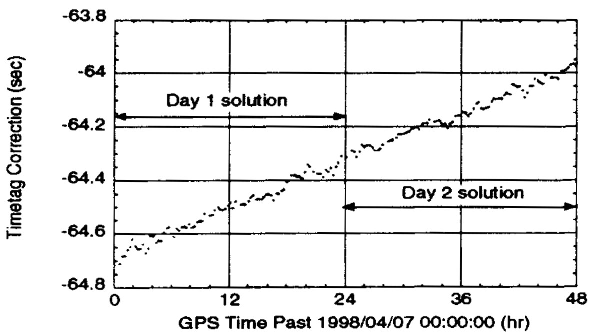

Figure 12. SNOE clock solution for two consecutive data segments

SUMMARY

The innovative microGPS architecture, a simplified flight receiver coupled with software designed to extract radiometric measurements and produce orbits, has been demonstrated to produce spacecraft orbits with ~75 meter accuracy. This performance is quite comparable to conventional GPS receivers that cost more, weigh more, and consume more power.